FERROALLOY OFF-GAS SYSTEMS: FROM DESIGN TO IMPLEMENTATION AND DESIGN VERIFICATION PROCESS

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ABSTRACT

This paper details the activities surrounding the design and verification of ferroalloy gas cleaning systems implemented for a number of ferroalloy furnaces located in Siberia, Russia. Yurga Ferroalloy Plant, a subsidiary of Kuznetskie Ferroalloys, has installed 2 new ferrosilicon furnaces over the past 2 years, for which new gas cleaning plants have been designed and installed, making use of a reverse air baghouse filter fitted with ePTFE membrane bags.

Detailed design work for the new off-gas systems at each smelter was completed, which included:

- *Complex furnace modelling leading to an off-gas volume.*
- *The off-gas volume was selected to ensure an optimal hood face velocity to keep the fume within the hood.*
- *Based on the off-gas volume, a system specification including equipment sizing and design was completed.*

The systems were built and commissioned. System testing and verification was done to ensure that the systems were operating according to the specified design. The main objectives of the after-implementation verification test work were:

1. To provide design verification, and therefore a level of confidence in the system design, considering all of the design and actual plant variables such as furnace power, feed mix and fan damper settings.

2. To ensure that the system is operating correctly and optimally.

This paper will describe the design, testing and verification processes, as well as report actual field results and design value comparisons.

KEYWORDS: *Off-gas system design, furnace predictive model, design verification.*

1. INTRODUCTION

Yurga Ferroalloy Plant (YURGA), a branch of JSC Kuznetsky Ferrosplavy, located in Yurga, Kemerova Province, Russia, is engaged with the construction of three new Ferrosilicon (FeSi) furnaces, numbered 63 to 65.

Furnaces 63 and 64 have already been put into operation. The furnaces are rated at 29 MVA and are producing FeSi75%.

Furnace off-gas systems are highly dependent on a range of variables and rarely operate under design conditions with off-gas energy variations of up to 40 % being generally accepted. Operational problems can occur if the air pollution control (APC) systems deviates too far from the design conditions in both higher and lower energy ranges.

2. DESIGN METHODOLOGY

In the past, off-gas system sizing was done using Specific Extraction (SE) data, which states extraction (Nm^3/h) per furnace energy input (kW), i.e. $Nm^3/h/kW$ as described by Rentz [1]. A more sophisticated method of sizing baghouse equipment is based on furnace heat extraction requirements – sometimes referred to as the "X" factor based on the furnace load (influenced by the amount and type of raw materials and furnace operation) as described in detail in a previous paper [2].

2.1. Furnace predictive model

In order to accurately predict the off-gas in terms of volume, temperature and composition, a furnace predictive model is generated which takes the following into consideration;

1. Furnace reaction gas is estimated through the utilisation of a carbon balance over the furnace.
2. The reaction gas is combusted and diluted with ambient air. Various amounts of dilution air are used to calculate the off-gas temperature profile.
3. Heat transfer correlations as described by Sieder and Tate [3], McAdams [4] and Cengel [5], are used to determine the temperature profile of the off-gas system and allow the estimation of baghouse inlet temperature.

The use and development of such a model has been described in detail in the previous articles Koekemoer et al [6], Els et al [7] and Els et al [8].

2.2. Furnace CFD

A computational fluid dynamics (CFD) model is constructed of the furnace and hood in order to verify that the extraction volume specified by the furnace predictive model is adequate to ensure that all furnace fumes are captured. The CFD model also indicates the predicted off-gas temperature, which should correspond with that predicted by the furnace predictive model.

3. YURGA SYSTEM DESIGN

3.1. Process description

New gas cleaning systems have been installed at furnaces 63 and 64 to ensure adequate extraction from the furnaces and eliminate atmospheric emissions through suitable filtration of the extracted off-gas. The gas cleaning systems are identical and are schematically illustrated in figure 1.

A brief description of the gas cleaning system at each furnace is:

- Each furnace hood is extracted via an off-gas duct to a set of cyclones (6-off at each gas cleaning system), where coarse particles and sparks are captured.
- A tapping fume fan serves to extract fumes generated at the furnace taphole. The tie-in point is on the emergency stack.
- Two ambient air dilution dampers are located, before the cyclone bank and the bag house to protect off-gas ducting and bags in the event of over-temperature.
- The bag house fitted with ePTFE membrane bags comprising of 12 compartments serves to remove particulate from the gas stream.
- Two fans after the baghouse propel gas through the system, followed by a stack to ensure adequate gas dispersion.

The baghouse compartments are cleaned by a reverse air fan, which extracts gas from the main fan inlet and reverses air flow through one compartment at a time.

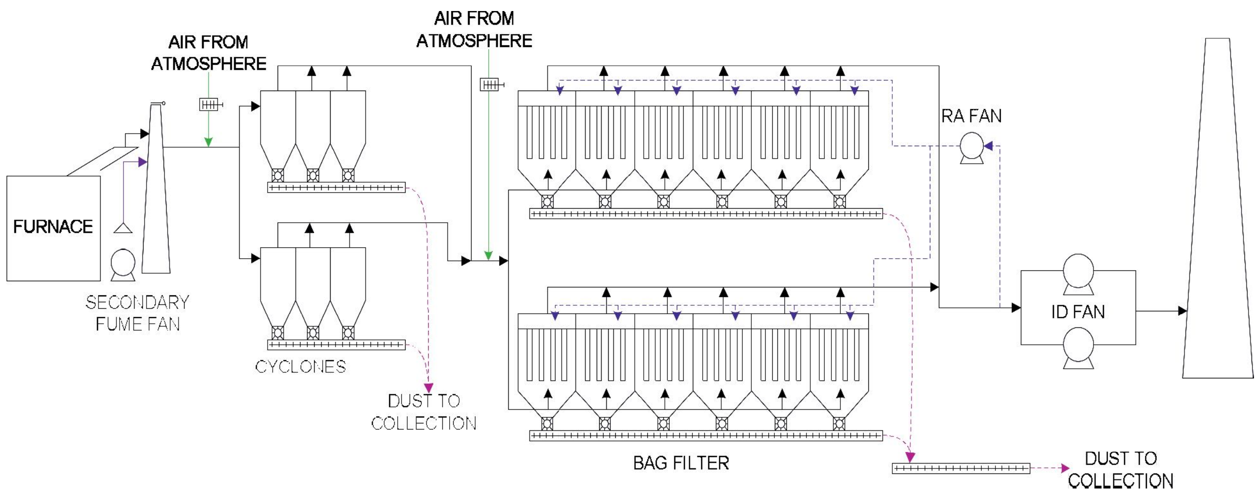

Figure 1: Basic off-gas system layout

3.2. Furnace operating base data

Both furnaces 63 and 64 are identical electric arc furnaces producing FeSi75% with an energy rating of 29 MVA and a total material feed rate of 9.53 ton/hr. The gas cleaning design catered for feed mixes with large variations in the ratio of coke to coal reductants.

The coal used is very reactive, with a high percentage of volatiles (up to 46%), when compared to more expensive reductants like coke. The volatiles do not contribute to the fixed carbon requirements of the reduction process and combust on top of the furnace bed leading to higher off-gas energies and volumes.

3.3. Design criteria and assumptions

The off-gas temperature must be designed to be within set limits; the upper limit is set to protect the furnace hood, off-gas ducting and the bags, whilst the lower temperature is governed by the specific acid dew point of the gas. At the design off-gas volume the furnace hood temperature must be below 450 °C and baghouse inlet temperature has to be kept below 260 °C and above the specific acid dew point of the gas

In reality, one finds that temperatures measured on site differ from modelling calculation values in that furnace hood temperatures tend to be a bit higher, caused by radiation heat. In-leakage of ambient air along the off-gas system also causes furnace hood temperatures to be still higher (less gas is actually extracted from the furnace) while reducing the baghouse inlet temperature (further dilution air is introduced by in-leakage).

Ambient temperatures varying from +40°C in summer to -54°C in winter were catered for by installation of two fans, which allowed significant flexibility in the furnace extraction flow rates.

3.4. Off-gas estimation results

The off-gas estimation results for both furnaces are shown in table 1 for results with both the tapping fume fan on and with the tapping fume fan off. During times of tapping when the tapping fan is on, less dilution air will be extracted at the furnace leading to higher off gas temperatures at a reduced extraction volume at the furnaces, but the same baghouse volumes and temperatures.

The furnace off-gas temperature and baghouse inlet temperatures for varying off-gas volumes are displayed in figure 2 for both conditions where the tapping fume fan is on and off. The baghouse temperature line can be seen as the process extraction requirement – i.e. at what baghouse normalised volume is the process constraint of maximum baghouse inlet temperature reached.

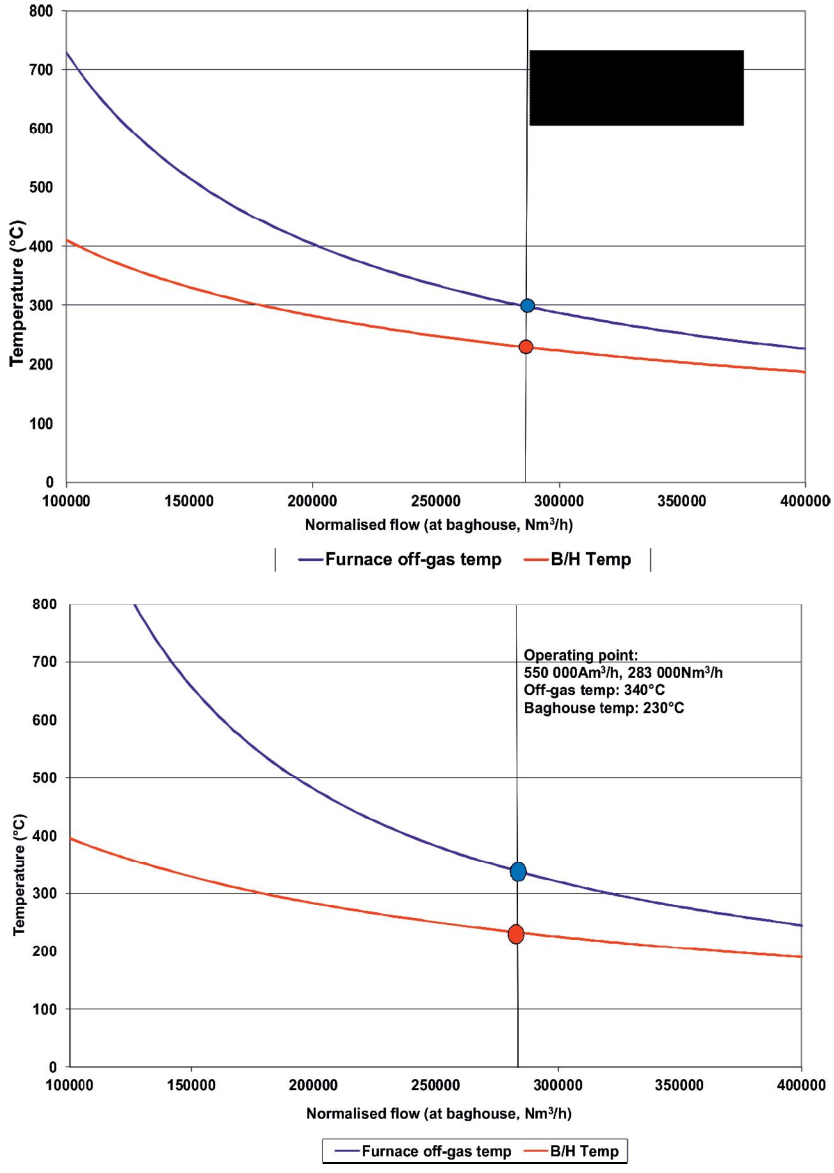

Figure 2: Off-gas model prediction with tapping fume fan on (left) and tapping fume fan off (right)

3.5. Cyclone design

Silica fume (SiO_2) collected at the baghouse can be sold at a premium if the purity of the product is high enough. The cyclones are installed to remove any furnace feed material carry-over that reduces the purity of the baghouse dust. In addition the very reactive coals can in some cases cause hopper combustion, which is prevented by pre-collection.

The off-gas systems for furnaces 63 and 64 contain six cyclones each, situated between the furnace and the bag house filter. The cyclone operating parameters are displayed in Table 2.

Table 1: Off-gas estimation results

Parameter	Unit	Tapping fan on	Tapping fan off
Reaction gas	kg/h	8 440	8 440
Furnace off-gas temperature	°C	340	300
Furnace off-gas volume	Am^3/h	574 000	622 000
Normalised volume	Nm^3/h	245 000	283 000
Tapping fume volume	Am^3/h	50 000	-
Baghouse inlet temperature	°C	230	230
Baghouse volume	Am^3/h	550 000	550 000
X-Factor	-	1.37	1.37

Table 2: Cyclone operating parameters

Parameter	Units	Value
Flow per cyclone	Am^3/s	28.8
Diameter of cyclone	m	3.5
Cyclone inlet velocity	m/s	18.8
Cyclone differential pressure	kPa	0.65

3.6. Filter emission

A 5 mg/Nm^3 emission level was guaranteed. At the stack volumetric flow of 569 250 Am^3/h, the emission rate is 1.6 kg/h. At the expected average off-gas particle concentration of 1.55 g/Nm^3 an overall system efficiency greater than 99.5 % is expected.

3.7. CFD design

Computational fluid dynamics (CFD) work was done to illustrate the effectiveness of the fume extraction system and to determine the furnace hood velocity as displayed in figure 3 and figure 4.

4. DESIGN VALIDATION

4.1. Flow testing results

Off-gas testing includes gas flow measurements, gas temperature measurements and gas composition measurements at various points along the off-gas ducting. All testing is done in accordance with the prescribed EPA methodologies [9]. The tested results are then compared to the design values, considering actual operating conditions.

The test results from the off-gas testing performed in December 2012 are shown in figure 5 and figure 6 for furnaces 63 and 64 respectively and compared to the design conditions.

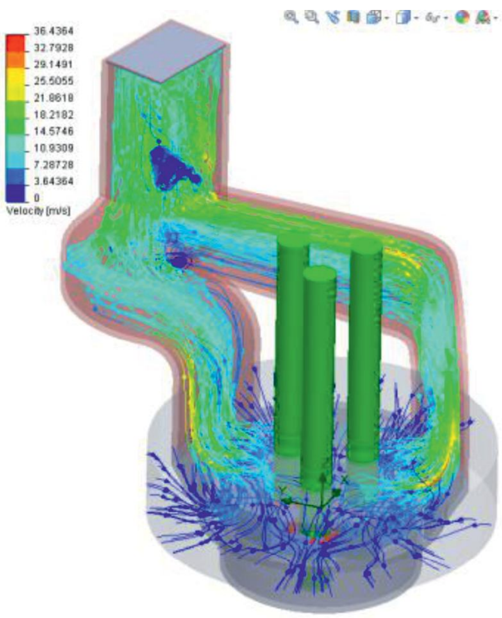

Figure 3: Elevation hood velocity

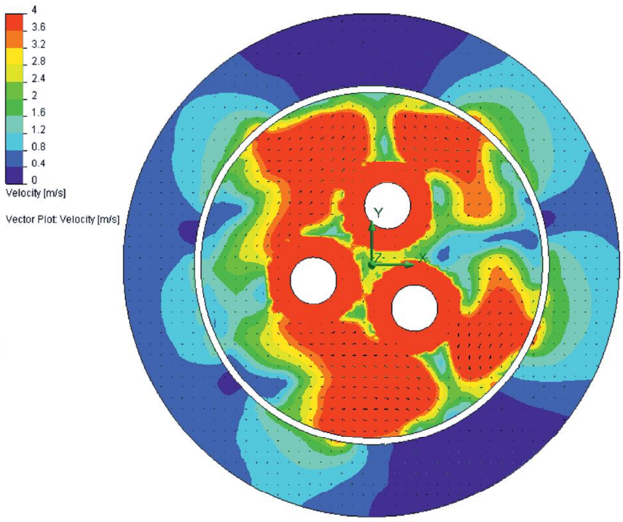

Figure 4: Hood plan view velocity

The following observations can be made from the test results:

- Lower than design ambient conditions led to a higher mass flow extraction rate and lower off gas temperatures at the same main fan damper settings.
- From the data it is clear that both off-gas systems are operating at normalised volumes higher than design with no visible fume leakages from the furnace hoods.
- This higher than design volume can lead to lower off-gas and bag house inlet temperatures, and the fan damper openings can be reduced slightly in order to increase the off-gas temperature.

In order to validate the design against test results, the off-gas process model has been adjusted to the current operating conditions; this includes ambient temperature and furnace charge mix. The comparison between the design values and the tested data are shown in figure 7. As can be seen in the graph, the tested data corresponds with the adjusted design conditions and thereby validates the off gas system.

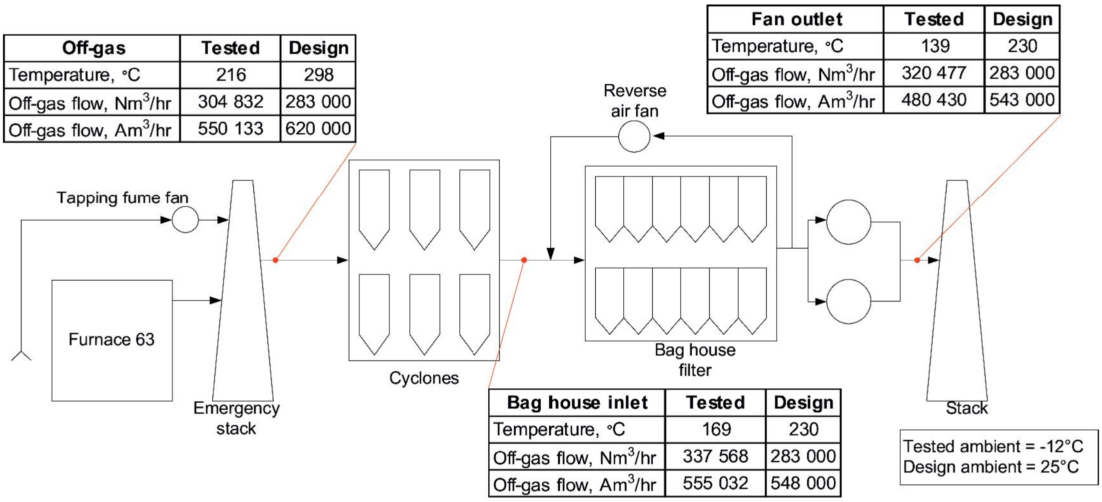

Figure 5: Flow testing results for Furnace 63

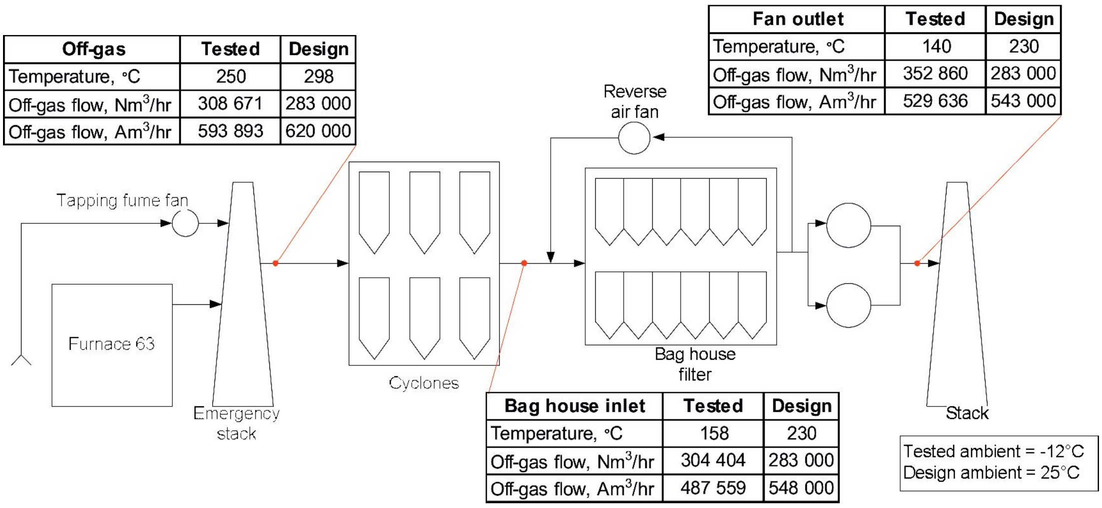

Figure 6: Flow testing results for Furnace 64

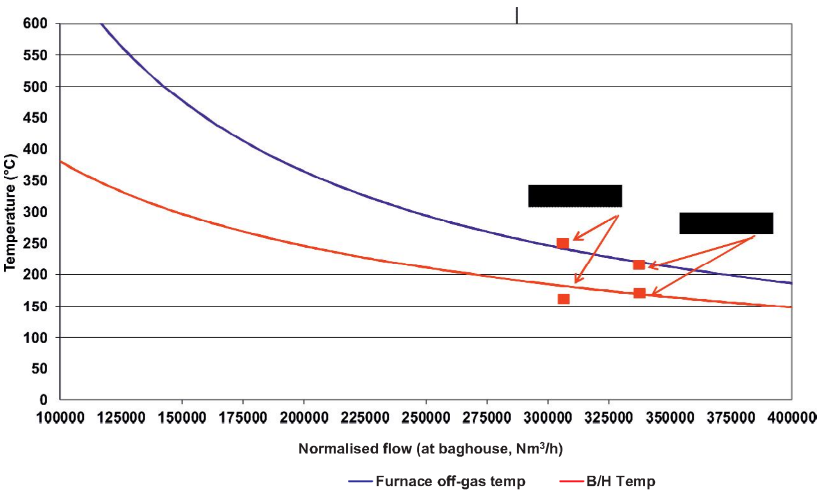

Figure 7: Off-gas design vs. tested conditions

4.2. Particulate efficiency results

Dust samples were collected in August 2012 from the cyclones and bag houses on the furnace 63 and 64 off-gas systems. The PSD of the dust collected for furnace 63 and 64 at both the cyclones and bag house as well as the calculated combined furnace PSD is displayed in figure 8.

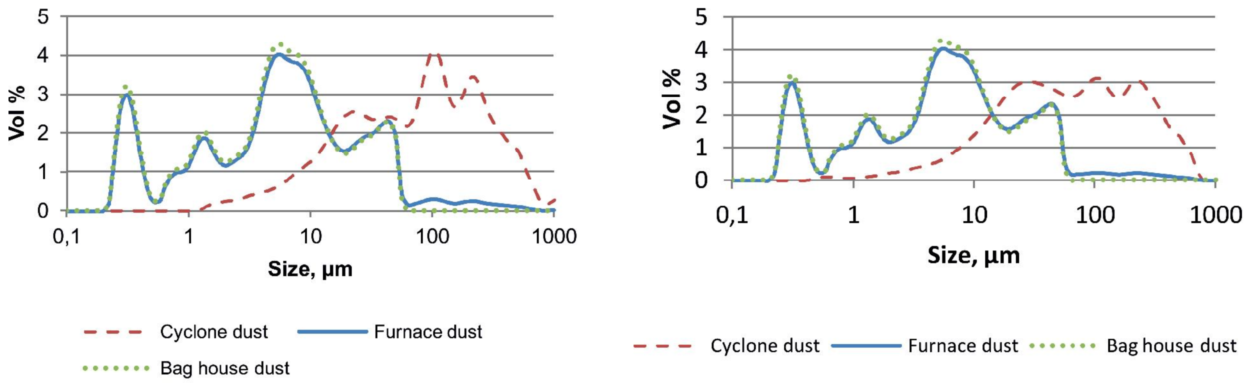

Figure 8: Furnace 63 (left) and furnace 64 (right) dust particle size distributions

The cyclones remove the majority dust of size above 10 µm, while the bag house filter removes the majority of dust of size 0.2 to 10 µm. The average particle size (D_{50}) for the furnace, cyclones and bag house is displayed in

.

Table 3: Particle size distribution

Location	Furnace 63	Furnace 64
(D_{50}) Furnace	5.98 µm	5.98 µm
(D_{50}) Cyclones	77.4 µm	57.5 µm
(D_{50}) Bag house	5.3 µm	5.3 µm

From table 3 it can be seen that the furnaces produce very fine fume with little feed material carry-over. The PSD displayed in figure 7 indicates a portion of dust in the range of 50 µm in the collected baghouse dust. It is believed these particles are actually a collection of smaller sized particles that passed through the cyclones and agglomerated in the baghouse hoppers. Some further work is still required on the particle size methodology and a chemical analysis on the baghouse dust was therefore performed to confirm the cyclone efficiency in removing larger particles. The chemical revealed a high quality silica fume product that compares well with the Elkem Microsilica Grade 940 product with more than 91 % SiO_2 and less than 1.0 % ignition loss.

The overall efficiency for both systems is displayed in table 4 and within range of the emission guarantee.

Table 4: Baghouse efficiency results

Baghouse	Flow rate (Am^3/h)	Emissions (mg/Nm^3)	Efficiency %
Furnace 63	508 680	3.23	99.7
Furnace 64	525 286	5.3	99.6

4.3. Differential drop measurements

Both furnace 63 and 64 were operating at a higher than design normalised flow rates during testing leading to a slightly higher pressure drop over the cyclones. The pressure drops were measured at 0.8 kPa for the furnace 63 cyclones and 1.0 kPa for the furnace 64 cyclones compared to the 0.65 kPa design.

Both baghouses have a setpoint to start the smart cleaning at a baghouse differential pressure of 2.0 kPa. Reducing the setpoint value on the smart cleaning system will lead to the filter being cleaned more often, but will result in a lower global pressure drop. The global bag house differential pressure is displayed in figure 9.

4.4. Filter drag comparison between membrane and connventional bags

Both bag houses 63 and 64 are equipped with membrane filter bags, in which the fine dust is filtered on an expended, micro-porous PTFE membrane. The filtration media remains clean in depth, allowing longer bag life, low pressure loss and low resistance to the flow. Person [10] has explained the relatively high filter drag of conventional woven fiberglass material, while Eriksen [11] and Stordahl [12] reported that GORE ® membrane/fiberglass filter media has a substantially lower filter drag than conventional media in metallurgical fume applications.

The typically measured values in these two bag houses are below 2.2 kPa, for a gross Air to Cloth Ratio of 49 $m^3/m^2/h$, ie a filter drag below 45 Pa. Conventional, non-membrane bags in ferroalloys applications return filter drags of 70-90 Pa, which means that one would have needed twice the higher filtration surface of non-membrane bags for the same flow and pressure loss.

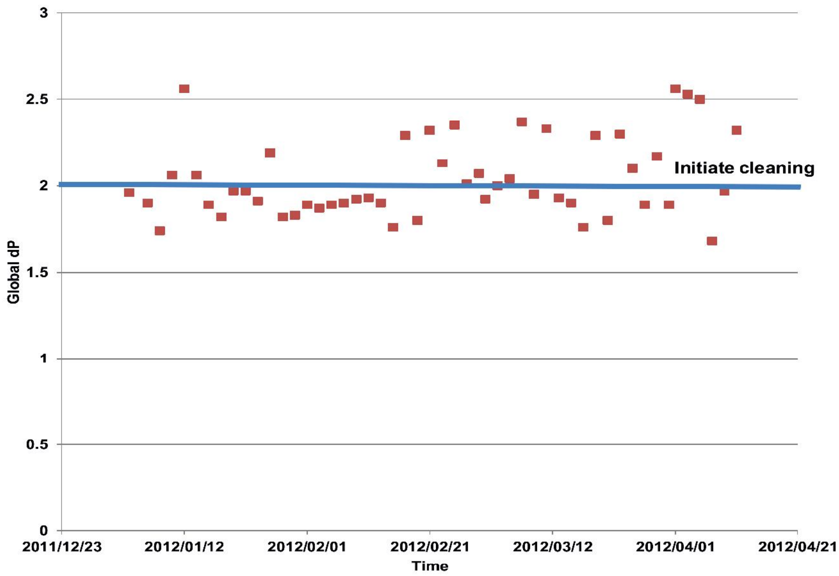

Figure 9: Global filter differential pressure

5. CONCLUSIONS

The following conclusions can be drawn:

- Off-gas systems can be optimally designed for widely varying furnace batch-mix scenarios. Careful consideration must be given to;

- o The design of ducting such that dust settlement does not occur at the various off-gas flow rates.
- o Selected off-gas temperature in order to ensure that the furnace hood is optimally extracted with no fume escaping the hood.
- o Design of equipment items such as cyclones, fans and bag house filters to ensure optimal sizing, pressure losses and operation over the entire range of off-gas volumes.
- o Design of fan system to cater for ambient temperatures varying from +40°C in summer to -54°C in winter.

- The furnace predictive model has been successfully validated against site data, collected through an on-going testing campaign.
- CFD analysis provides an efficient tool to ensure that the furnace fume is adequately contained in and extracted from, the furnace hood.

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